Neutrino-nucleus interactions: open questions and future projects

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We discuss various issues concerning the interactions of nuclei with neutrinos of low impinging energies (i.e. having several tens of MeV to a few hundred MeV) of interest for particle physics, nuclear physics and astrophysics. We focus, in particular, on open questions as well as possible strategies to obtain more experimental information. The option of a low-energy beta-beam facility is extensively discussed. We also mention its potential concerning the neutrino magnetic moment.

1. Introduction

Neutrino-nucleus interactions are a topic of current great interest. The motivations for studying such reactions come from the necessity of knowing precisely neutrino detector response since nuclei are often used as neutrino detectors e.g. in solar experiments, for supernova observatories or in oscillation measurements. Another important motivation comes from astrophysics and, in particular, from understanding the nucleosynthesis of heavy elements during the r-process [1,2,3,4,5,6] or from neutrino-nucleosynthesis [7,8,9,10].

The present knowledge of ν-nucleus interactions exploits the knowledge of the weak interaction on one hand and the most developed techniques for describing the nucleus on the other hand. The models employed take advantage of a wealth of indirect as well as direct experimental information. The latter represent, however, a limited ensemble of data still. Useful indirect information is provided by related processes like beta-decay, muon capture, electron scattering or charge-exchange reactions. Some model-independent sum-rules also help in constraining the calculations. The direct measurements include one measurement on deuteron [11] and iron [12] and a series a measurements on carbon [13] with neutrinos produced by the decay-at-rest of muons or by the decay-in-flight of pions.

By performing systematic neutrino-nucleus interactions studies one could address the numerous open questions in this field [4,5,14,15]. First, a very precise knowledge of the interactions on some nuclei, which are currently used as neutrino detectors, is needed. Here we mention a few. The best known case is the neutrino-deuteron reaction, relevant for the SNO experiment [16], where theoretical calculations reach the few percent precision [17]. However, there is still an important unknown quantity $L_{1,A}$ whose determination would improve our knowledge of the pp reaction in the Sun. The most studied case, namely neutrino interactions on carbon, still suffer from a discrepancy between experiment and theory, in particular for the neutrinos produced from the decay-in-flight of pions, in spite of the efforts done during several years [18]. A precise measurement of the reactions on oxygen is of great interest also in view of the next-generation experiments involving Megaton detectors like Hyper-K or UNO [19]. In particular, their use with the aim of studying CP violation in the lepton sector would need a very precise determination of the reaction cross sections in the range of several hundred MeV. Lead represent an interesting nucleus as well, e.g. for supernova observatories [20,21,22,23,24]. In this context, the precise measurement of the differential cross sections of electrons emitted in charge-current events would be very useful, since their measurement would give us precious information on the neutrino temperatures at emission, if a core-collapse supernova explodes [23].

One of the richnesses of this field is that for increasing neutrino energies, neutrinos probe the nuclear to the nucleon degrees of freedom. While the description of the low-energy regime exploits approaches like the Elementary Particle Theory, Effective Field Theories, or microscopic models, such as the shell model or the Random-Phase-Approximation, the Fermi Gas is the basis for the theoretical description in the high energy regime. In particular, neutrinos can be used to perform nuclear structure studies since neutrinos probe nuclear excited states for which little or no experimental information is available (Figure 1) [22]. The role of some of these states in astrophysical contexts is outlined in several papers [1,20,22,25,26]. A larger ensemble of experimental data would put the interpolation, of the neutrino-nucleus interaction modeling between these two regimes, on even more solid grounds. This would also help the extrapolation to the case of neutron-rich nuclei of astrophysical interest that are not experimentally accessible.

In order to address these (and other) open questions, one needs a facility producing intense low-energy neutrinos. Note that the Minerνa proposal would address interesting issues on neutrino-nucleus interactions with energetic neutrinos [27].

2. Strategies

There are essentially two options for a facility producing low-energy neutrino beams: either a conventional one, based on the decay of pions and muons, or beta-beams [28]. The former was the object a few years ago of a proposal, i.e. ORLAND (Oak Ridge LAboratory for Neutrino Detectors) [29] and is now taking a new shape [30]. The latter is a recent proposition [28], based on a novel method to produce neutrino beams, which exploits the acceleration of nuclei that decay through beta-decay [31]. The neutrino beams obtained with these two options present complementary features both for the flavour content and for the energy. Conventional sources provide us with neutrinos of different flavours, while beta-beams produce pure electron neutrino (or anti-neutrino) beams. As far as the energy

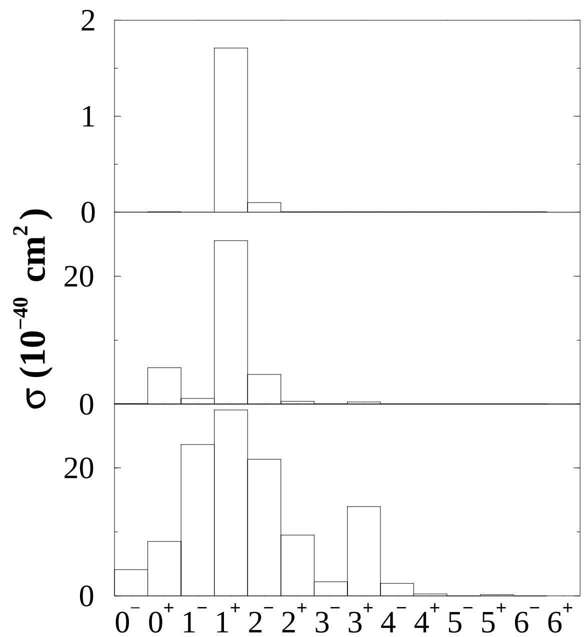

Figure 1. *Cross section of the* $^{208}Pb(\nu_e, e^-)^{208}B$ *reaction*: The figure shows how the relative contribution of states excited in the reaction and having different multipolarity increases, for increasing neutrino energy, namely for $E_\nu = 15$ MeV (up), 30 MeV (middle), 50 MeV (bottom) [22]. Note that little experimental information is available on the J^π=$0^-, 1^-, 2^-$ states and none on those having higher multipolarity.

is concerned, muon decay furnish neutrinos with a Michel spectrum peaked at about 35 MeV and having maximum energy of about 50 MeV. Beta-beams have the specific feature that the neutrino mean energy depends on the ion acceleration according to $E_\nu \simeq 2\gamma Q_\beta$, where γ is the Lorentz gamma factor and Q_β is the beta-decay Q-value. Therefore the neutrino energy range can be varied by varying the γ of the decaying ions. A detailed comparison for the specific case of the lead is made in [32].

2.1. Low-energy beta-beams

Two possible scenarios can be envisaged for a low-energy beta-beam facility [28] where it is part either of one of the future nuclear laboratories (or projects) for the production very intense exotic ion beams (like e.g. GSI, GANIL, EURISOL or RIA), or of the high energy beta-beam facility at CERN. For the former case, there are several requirements which should be met. Two essential aspects are the ion intensity which can be attained and the availability of a ring to store the ions. Let us mention a few cases as typical examples. The future GSI facility [33] includes a storage ring and the ions will be accelerated to GeV energies, producing neutrinos having a few tens of MeV. However, the fragmentation method used to produce the ions will give at maximum 10^9 ν/s. At GANIL, the ISOLDE technique employed will allow to reach 10^{12} ν/s but no storage ring is planned, so that the ions can be eventually used as a neutrino source at rest. As far as the high energy beta-beam facility at CERN is concerned, according to the first baseline scenario, the beams are accelerated to several tens of GeV per nucleon and stored in a storage ring with long straight sections [31,34]. The beams are fired to a gigantic Cherenkov detector [19], located in an upgraded Fréjus Underground Laboratory, with the aim of studying very small values of the neutrino mixing angle θ_{13} and CP (and T) violation in the lepton sector [31,35]. Other interesting scenarios are now proposed where beta-beams would have even higher energies and would be sent to further distances, like e.g. the Gran Sasso Laboratory [36,37]. If such a facility is built, low-energy neutrino beams would be available and could be fired to a detector located close to the storage ring.

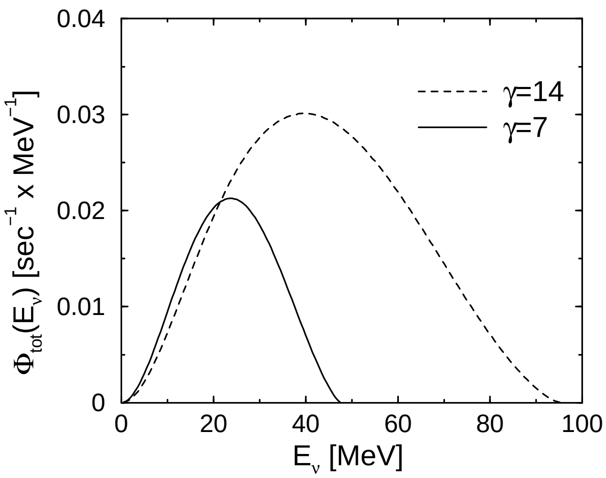

Figure 2. *Neutrino fluxes at a low-energy beta-beam facility [38]:* The results shown are obtained using Eq.(2-4) and correspond to ^{18}Ne, as a beta-emitter, boosted to two different Lorentz factors.

It is important to emphasize that a rich physics program can be performed, if such beams are available [15,28,29], neutrino-nucleus interaction studies being one of the possible axis of research [28,38]. Here we also describe the potential as far as the neutrino magnetic moment is concerned [39].

3. Neutrino-nucleus interaction rates

We present the rates that can be attained at a low-energy beta-beam facility. The total number of events per unit time is given by [38]:

$$\frac{dN_{ev}}{dt} = g\tau nh \times \int_0^\infty dE_\nu\, \Phi_{tot}(E_\nu)\, \sigma(E_\nu)\,, \qquad (1)$$

where n is the number of target nuclei per unit volume, g is the number of injected ions per unit time, τ the half-life of the parent nucleus, $\sigma(E_\nu)$ the relevant neutrino-nucleus interaction cross-section as a function of neutrino energy. The neu-

trino flux $\Phi_{tot}(E_\nu)$ is obtained by integrating over the useful decay path of the storage ring and over the volume of the detector:

$$\Phi_{tot}(E_\nu) = \int_0^D \frac{d\ell}{L} \int_0^h \frac{dz}{h} \int_0^{\bar{\theta}} f(\theta)\Phi_{lab}(E_\nu, \theta), \quad (2)$$

with

$$\tan\bar{\theta}(\ell, z) = \frac{R}{d+\ell+z}\,, \quad (3)$$

and

$$f(\theta) = \frac{\sin\theta d\theta}{2}, \quad (4)$$

where θ is the angle of emission with respect to the beam axis, L the total length of the storage ring with straight sections D, R is the radius of the cylindrical detector of depth h placed at distance d from the storage ring. The full expression for the boosted flux Φ_{lab} is given in [38]. Figure 2 shows the neutrino fluxes used.

Table 1 presents the results obtained for four nuclei as typical examples, i.e. deuteron, oxygen, iron and lead. Note that the rates shown are obtained by considering realistic ion intensities, namely 2×10^{13} $\bar{\nu}$/s (from ^{6}He decay) and 8×10^{11} ν/s (from ^{18}Ne decay), as obtained in the first feasibility study [34]. An efficiency of 100% is considered for all cases. Final rates will be given by detailed simulations of the detector response taking into account possible backgrounds. The differences in the ν and $\bar{\nu}$ rates are due both to the cross sections and to the different ion intensities at production.

In order to show how the number of events changes as a function of the storage ring length, two scenarios are envisaged, where the detector is placed close either to a small or to a large storage ring. We take as typical sizes those of the ring planned for the future GSI facility [33], and of the one considered in the beta-beam baseline scenario at CERN [34]. Note that in [38] an analytical formula is given which allows one to scale the present exact rates for storage rings of different lengths. In fact, for a close detector as is the case here, the rates do not simply scale as L/D, like for a far detector, due to the anisotropy of the flux.

From Table 1 one can see that interesting interaction rates can be achieved by using typical parameters available from existing feasibility studies.

3.1. Prospects for the neutrino magnetic moment

The indirect evidence that neutrinos are massive particles, provided by oscillation experiments, implies that neutrinos have a small magnetic moment. In the case of a Dirac mass, standard model interactions give the neutrino a magnetic moment of $3 \times 10^{-19}(m_\nu/\mathrm{eV})$ in units of Bohr magnetons, μ_B. The observation of a large magnetic moment would indicate interactions beyond the Standard Model and provide valuable information for understanding the neutrino mass mechanism. So far, the best limits from direct measurements have been obtained with reactor experiments and are in the range $\mu_\nu < 1.0 - 4 \times 10^{-10}\mu_B$ at 90 % C.L. [41]. Similar upper bounds have recently been deduced from solar events [42]. Indirect limits in the range $10^{-11} - 10^{-12}\mu_B$ have been obtained by using astrophysical considerations [43], although the exact values for these limits are model-dependent (for a review see [44]).

The direct measurements exploit neutrino-electron scattering where the neutrinos are detected by measuring the recoil of the electrons. In fact, if the magnetic moment is non-zero an extra electromagnetic term adds to the cross section [41]:

$$\left(\frac{d\sigma}{dT}\right)_M = \frac{\pi\alpha^2\mu_\nu^2}{m_e^2}\frac{1-T/E_\nu}{T}, \quad (5)$$

where T is the electron recoil energy, m_e is the electron mass. One can see that a non-zero neutrino magnetic moment dominates the neutrino-electron cross section particularly for very low electron recoils ($T \to 0$). This fact is exploited in direct measurements to set a limit on μ_ν.

Here we present the potential of a low-energy beta-beams facility [39]. The ions are used as an intense neutrino source at rest. To improve present direct limits on the neutrino magnetic moment one needs : *i)* very intense neutrino sources of well-known fluxes; *ii)* very low threshold detectors. Such detectors are currently in-

Table 1

Reaction	Ref.	Mass (tons)	Small Ring (L=450 m, D= 150 m)	Large Ring (L=7 km, D=2.5 km)
ν+D	[14]	35	2363	180
$\bar{\nu}$+D	[14]	35	25779	1956
$\nu+^{16}$O	[40]	952	6054	734
$\bar{\nu}+^{16}$O	[40]	952	82645	9453
$\nu+^{56}$Fe	[24]	250	20768	1611
$\nu+^{208}$Pb	[23]	360	103707	7922

Neutrino-nucleus interaction rates (events/year) at a low-energy beta-beam facility [38]: Rates on deuteron, oxygen, iron and lead are shown as examples. The rates are obtained using Eqs.(1-4) with $\gamma = 14$ as boost of the parent ion. The neutrino-nucleus cross sections are taken from referred references. The detectors are located at 10 meters from the storage ring and have cylindrical shapes (R=1.5 m and h=4.5 m for deuteron, iron and lead, R=4.5 m and h= 15 m for oxygen, where R is the radius and h is the depth of the detector). Their mass is indicated in the second column. Rates obtained for two different storage ring sizes are presented (L is the total length and D is the length of the straight sections). Here 1 year = 3.2×10^7 s.

vestigated [45]. Clearly in this case - as for a static source [45,46,47] - the neutrino fluxes can be very accurately calculated. Figures 3 and 4 show the number of neutrino-electron scattering events as a function of electron energy recoil. The results are obtained by averaging the total (weak and electromagnetic) cross section with the neutrino fluxes produced by collecting 10^{15} ^{6}He/s inside a 4π detector (such intensities might be attained with further feasibility studies [48]). A 100% efficiency is assumed. If there is no magnetic moment, this intensity will produce about 170 events in the 0.1 MeV to 1 MeV range per year and 3 events in the 1 keV to 10 keV range per year. These numbers increase to 210 and 55 respectively in the case of a magnetic moment of $5 \times 10^{-11}\mu_B$. This indicates that the present direct limits might be improved by almost an order of magnitude, the precise value requiring a detailed simulation of the detector response.

4. Conclusions and Perspectives

The availability of low-energy neutrino beams would offer the opportunity to tackle interesting open issues on neutrino-nucleus interactions of interest for various domain of physics. The option of a low-energy beta-beam facility seems a very promising one. For these low energy applications it would be of great interest to investigate if, at least for one beta-beam emitter, higher ion production rates, than the ones obtained in the first feasibility study, can be achieved. In the coming years a detailed feasibility study of the low-energy as well as the high-energy beta-beam facility will be performed within the context of the European Isotope Separation On-Line Radioactive Ion Beam Facility (EURISOL) project.

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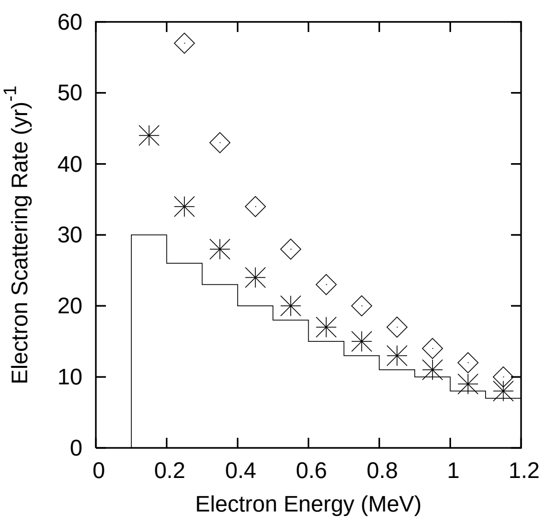

Figure 3. *Prospects on the neutrino magnetic moment [39]:* The figure shows the number of neutrino-electron scattering events. ^{6}He is the beta-beam emitter produced at the rate 10^{15} per second, and collected inside a 4π detector. (Similar results are obtained if ^{18}Ne is used instead.) The results shown corresponding to electron recoil energies of [0.1,1.2] MeV are shown. The diamonds show the number of scatterings if the neutrino has a magnetic moment of $\mu_\nu = 10^{-10}\mu_B$, the stars present the number of events if $\mu_\nu = 5\times10^{-11}\mu_B$. The histogram shows the expected number of events for a vanishing neutrino magnetic moment.

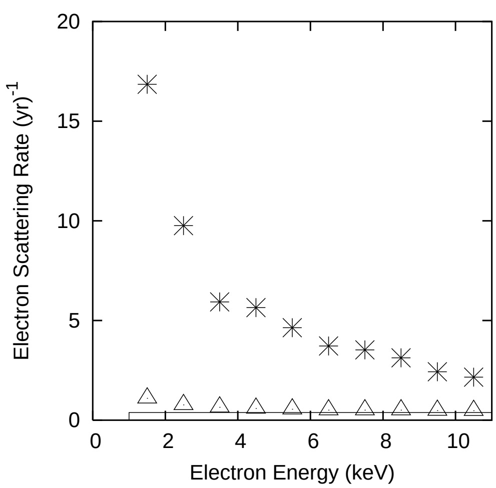

Figure 4. Same as Figure 1 but for electron energy recoils within [1,10] keV. The triangles give the number of events if the neutrino has a magnetic moment of $\mu_\nu = 10^{-11}\mu_B$.

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